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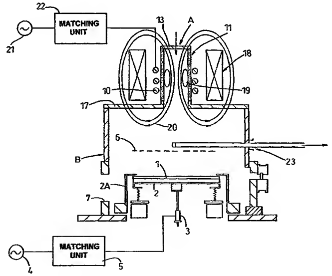
(54) Title: PLASMA PROCESSING APPARATUS




(57) Abstract: A solenoidal magnetic field generated by a coil (18) around the upper chamber (A) acts as a magnetic plasma attenuator. By judicious adjustment of the magnetic field strength, a dense plasma region (19) forms inside the tube (11) and adjacent to an antenna (10) and is at least partially trapped by the field lines (20). These field lines intersect the wall of the upper chamber (A) near or on the lid (13), and either on the upper chamber wall near its base, or on the lid (17) or upper walls of the lower chamber (B). Significant numbers of radicals can be created in the upper chamber (A), which then diffuse into the lower chamber. The associated ion flux is reduced, however, because of the losses where the field lines intersect the walls, thereby ensuring that the ratio of ion numbers to radical numbers reaching the wafer is reduced.

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"Plasma Processing Apparatus"

Plasma may be produced in a first chamber, with the ions and radicals created being allowed to diffuse into a second chamber where etching of, or deposition on, a silicon wafer or other workpiece may take place. This is the concept of a de-coupled plasma source and process chamber. It is frequently advantageous to produce a dense plasma so that there are large numbers of radicals available to increase the rate of the required chemical process, etch or deposition. However, in general, when a dense plasma is created, in addition to a large number of radicals, large numbers of ions will be produced which may contribute to damage of or other undesirable effects on a silicon wafer or other workpiece.

It is an object of this invention to provide means whereby the ratio of radicals to ions can be controlled such that a reduction in the proportion of ions reaching the workpiece may be reduced.

According to a first aspect of the invention there is provided a plasma processing apparatus comprising a first chamber provided with a plasma inducing device designed to produce a plasma in said first chamber, and a second chamber into which plasma so produced can diffuse to act upon a workpiece being processed, and a magnetic field production device positioned relative to at least the first of said two chambers and constructed to cause attenuation of the ions which diffuse into the second chamber and

approach the workpiece, by directing a proportion of the ions to a loss surface of either chamber.

The control measures incorporated into the system by the magnetic field device, adjust the relative numbers of ions to radicals, which diffuse into the second chamber and reach the wafer. Thus, the use of suitably orientated magnetic fields will influence ion diffusion while not affecting the diffusion of neutral radicals.

Preferably the magnetic field production device would comprise permanent magnets or electromagnets installed around the side wall of the first chamber. The magnetic field production device around the first chamber could be a solenoid whose output can be varied.

The apparatus could incorporate an additional plasma inducing device at the upper region of the second chamber. In that case permanent magnets, electromagnets or a solenoid may be installed also around said additional plasma inducing device at the upper region of the second chamber, as a further magnetic field production device

Another possibility is that the magnetic field production device comprises a magnetic structure formed at the junction of the two chambers to create a dipole magnetic field there.

The apparatus could incorporate a ring gas feed within the second chamber, below the junction point of the two chambers, in addition to a gas feed inlet to the top of the first chamber.

A solenoid device whose output can be varied may be provided for the second chamber at a position to create a magnetic field inside the second chamber at the level of the workpiece to steer ions towards the workpiece.

The first chamber could be of annular form with the magnetic field production device comprising separate permanent magnets, electromagnets or solenoids located both within and around said annulus.

The first chamber might be formed of two or more differing-diameter cylindrical dielectric sections, one above the other, each such section being provided with its own plasma inducing device.

The second chamber can be provided with a magnetic bucket arrangement created by an array of magnets around the chamber wall.

The first chamber geometry could be formed as a cylinder, a stepped cylinder, a cone, a truncated cone, or a hemisphere, or a combination of these geometries.

According to a further aspect of the invention there is provided a plasma processing apparatus comprising a first chamber provided with a plasma inducing device designed to produce a plasma in said first chamber, and a second chamber into which plasma so produced can diffuse to act upon a workpiece being processed, wherein the first chamber is formed of two or more differing-diameter cylindrical dielectric sections, one above the other, each

such section being provided with its own plasma inducing device.

The portions joining the individual sections of said first chamber are ideally formed of metallic or dielectric material and may be positioned perpendicular to or angled to said sections.

The multi-section first chamber can have a magnetic field production device associated with more than one of said sections, each constructed to cause attenuation of the flux of the ions which diffuse into the second chamber and approach the workpiece.

Further annular forms of a first chamber with pairs of attenuation magnetic field production devices positioned concentrically of one another, could be provided to enable processing to be undertaken over a wide area.

Ideally said first chamber will incorporate a dielectric plasma tube formed from aluminium nitride or silicon carbide or other dielectric material having a thermal conductivity sufficiently greater than aluminium oxide to allow high power operation without failure-inducing high thermal gradients arising in the dielectric material.

In order to increase the area of processing activity, a plurality of said first chambers of the form of this invention could be provided across the top of the second chamber.

The invention further extends to a plasma processing apparatus comprising a first chamber provided with a plasma inducing device designed to produce a plasma in said first chamber, and a second chamber into which plasma so produced can diffuse to act upon a workpiece being processed, wherein said first chamber incorporates a dielectric plasma tube formed from aluminium nitride or silicon carbide or other dielectric material having a thermal conductivity sufficiently greater than aluminium oxide to allow high power operation without failure-inducing high thermal gradients arising in the dielectric material.

The control measures may be required to have a functional dependence on time or another parameter, which may be linked to a particular aspect of the etch or deposition process. For example the number of ions reaching a surface being etched may be required to decrease once a surface layer has been removed, while the number of radicals reaching the surface may be required to remain constant. The level of the control measures can be re-adjusted after a given time in which the surface layer has been removed, in order to achieve the new desired ratio of radicals to ions. The control measures may also incorporate a spatial dependence, so that the relative number of ions to radicals can be varied as a function of position on the wafer.

For the etching of deep trenches in silicon or other suitable materials, a switched process may be used (Robert

Bosch GmbH US5501893 or Surface Technology Systems Ltd US6051503). In such a process, alternating steps of material deposition and etch occur, with the resultant anisotropic etching of features into the wafer. In greater detail, a polymer is deposited on both the sides and bottom of a trench or other feature during the deposition step. During the following etch step, the polymer is preferentially removed from the bottom of the trench by directed ion bombardment, then allowing a chemical etch of the exposed silicon. Although the chemical etch is essentially isotropic, the overall etch process is anisotropic, because the polymer removal is only from the bottom of the trench, and the silicon etch depth is small for each etch step. A suitable patterned mask of, for example, photoresist is applied to the wafer before the etch process is started in order to define the surface geometry of the features to be etched. It is an important aspect of the overall process, particularly for deep trench etching, that the ion bombardment utilised to remove the polymer from the bottom of the trench, does not erode the mask before the required depth of etch has been achieved, otherwise the definition of the features will be lost.

A number of different arrangements of permanent and electromagnets have been described in our International Patent Application PCT/GB99/04168, to allow control of the relative numbers of ions to radicals which are permitted to reach the wafer. In regard to a switched etch process, the

field produced by any electromagnet may be adjusted to one level for the etch step and to a different level for the deposition step. In some circumstances it may be advantageous to vary the field strength during either or both of the etch and deposition steps. For example during the etch step, the magnetic field strength may be kept low during the early part, in order to allow a high flux of ions to reach the wafer and remove the polymer which has been deposited on the bottom of a trench. When the polymer has been removed, the field strength can be increased to reduce the ion flux to the wafer and so reduce the mask etch rate. In addition to this, the field may be adjusted from one etch step to the next etch step, and/or from one deposition step to the next deposition step, in order gradually to adjust the relative numbers of ions to radicals as the trench etch proceeds.

This Application describes in detail, features of a plasma processing apparatus which enable a high etch rate to be achieved with good uniformity in the etch rate across the wafer and precise control of the shape of etched features. In this Application, the description is particularly directed towards etching carried out by means of a switched process as described above. This is not intended to preclude the application of aspects of the system to either a continuous etch process or a continuous deposition process (the term "continuous" in this context referring to the feature that the process is "not switched

between etch and deposition steps", rather than any implication that the process rate, or other aspect, remains constant in time).

The plasma processing apparatus consists of two or more chambers. In the second chamber, usually the larger, a silicon wafer or workpiece is mounted on a suitable support. This support may incorporate features to allow cooling or heating of the wafer during, before or after processing. The support may also allow an RF or DC voltage, continuous or pulsed, to be applied to the wafer with respect to the chamber, to enable ions to be accelerated to the wafer. Features may be incorporated in the support and in the chamber wall to allow remote loading or un-loading of the wafer. Ports will usually be incorporated in the walls of this chamber for pressure gauges and other diagnostics, with a relatively large port or ports through which gas exits to the vacuum pumping system used to maintain the desired operating pressure in the chamber.

The first chamber or chambers will typically be of smaller volume than the second chamber in which the wafer is mounted. Plasma is created and sustained in this first chamber and ions and radicals diffuse into the second chamber. Control means, such as a magnetic attenuator, may be used to define the flow of ions and radicals into the second chamber. Reference to one chamber does not preclude the use of multiple chambers in which plasma is formed, with multiple control means to control the flow of ions and

radicals into the second chamber in which the wafer is mounted. When plasma is formed in multiple first chambers there is no restriction implied on whether all chambers are operating at the same time, whether feed gases are the same, or whether the level of power input to each plasma is the same.

From a still further aspect of the invention there is provided a method of controlling the transmission of a plasma to a workpiece, wherein plasma is created in a first chamber provided by a plasma inducing device, and is allowed to diffuse into a second chamber to act upon a workpiece being processed, and an attenuation magnetic field production device positioned relative to at least the first of said two chambers is operated in a manner to cause attenuation of the ions which diffuse into the second chamber and approach the workpiece, by directing a proportion of the ions to a loss surface of either chamber.

The invention may be performed in various ways and preferred embodiments thereof will now be described, by way of example with reference to the accompanying drawings, in which:-

Figure 1 is an illustration of a form of de-coupled plasma source and process chamber of this invention;

Figure 2 is a horizontal cross-section through the chamber of Figure 1;

Figures 3A to 3C illustrate possible alternative geometries for the shape of the first chamber of the system shown in Figure 1;

Figure 4 shows a further possible geometry for the first chamber of the system in Figure 1 and a magnetic field created therein;

Figure 5 shows the magnetic field created in a modified form of the system in Figure 1;

Figures 6, 8 and 9 illustrate modified versions of the apparatus as shown in Figure 1; and

Figure 7 shows analysis results of experimentation using the apparatus of Figure 6.

The system of a single first chamber A in which plasma is produced and allowed to flow into the second chamber B, in which the wafer is located, is shown diagrammatically in Figure 1. The wafer 1 is mounted on a wafer support 2 in the lower chamber B. Good thermal contact is maintained between the wafer and a temperature-controlled section of the support by means of mechanical clamping 2A of the wafer, or by electrostatic clamping, or by other means appropriate to the situation. A thin layer of pressurised gas such as helium, injected through an inlet 3, may be used to fill the small gap between the back of the wafer and the support 2 in order to improve the conduction of heat between the two surfaces. The appropriate parts of the support may be connected to an RF or DC, continuous or pulsed voltage, power supply, for example the RF supply 4,

via a suitable impedance matching unit 5, to create a controlled potential difference across the sheath formed above the wafer, thereby controlling the energy of ions impinging on the wafer. The normal processing height within the chamber is indicated at 6. Gas is evacuated through a pumping port 7.

Permanent magnets 21 (as shown in Figure 2) may be installed around the perimeter of chamber B (and chamber A if appropriate) in columnar form to define a "magnetic bucket". A "multi-cusp" or "picket fence" arrangement serves to reduce the diffusion of ions and electrons to the walls of the chamber. Historically a "magnetic bucket" configuration has been utilised to increase the plasma density within a chamber because, for a given rate of production of ions and electrons within the volume, the rate of loss to the walls is reduced compared with the situation in which the "magnetic bucket" is not present. If magnetic confinement is provided for chamber A, it is primarily to serve this purpose and allow a high density plasma to be formed with a high density of neutral radicals.

Where there is a requirement to reduce the number of ions reaching the wafer compared with the number of radicals, it would at first sight appear illogical to add magnetic confinement to chamber B, since those ions which diffuse into chamber B will be confined more effectively than if the "magnetic bucket" had not been present. For

chamber B, however, the purpose of providing magnetic confinement is primarily to increase the uniformity of the ion flux that reaches the wafer. With no magnetic confinement around chamber B, diffusion of plasma from chamber A down into chamber B, results in ions and electrons being lost to the walls of chamber B, before reaching the wafer position. The plasma density decreases with distance from chamber A to the wafer, and becomes increasingly non-uniform, with the highest density on the axis of the chamber. Magnetic confinement around chamber B reduces the loss of plasma to the walls, and therefore ensures that the uniformity of the plasma at the wafer position is considerably increased. The proposal for magnetic confinement around chamber B is not intended to preclude the use of a system in which there is no magnetic confinement around chamber B. That is the "magnetic bucket" is only utilised when there is an advantage in so doing.

In order to obtain high numbers of neutral radicals at the wafer position, with low numbers of ions, but with good spatial uniformity of the ions, it is necessary to provide good confinement of ions within chamber B, but at the same time significantly reducing the number of ions diffusing out of chamber A compared with the number of radicals. A magnetic plasma attenuator integral with chamber A, or between the two chambers, can be used in conjunction with the plasma confinement in chamber B to achieve the required result. A dipole magnetic plasma attenuator for this

purpose may be formed by a permanent magnet or electromagnet.

At the level where the wafer is processed, a solenoidal magnetic field is desirably formed inside the chamber B by an electromagnet 9 located either outside (as shown) or inside of the chamber. The strength of the field may be controlled such that it is of a different value during separate steps of a switched process, and in addition may be ramped in value either up or down for either respective step as the process progresses. The purpose of this field is to assist in the control of the directionality of the ions reaching the wafer surface and in the uniformity of the ion flux across the surface of the wafer.

The process plasma is formed in the upper chamber A. For the remainder of this description reference will be to a plasma created and sustained by the inductive coupling of radio frequency power. This does not, however, preclude the use of other means to form the plasma, such as by the use of microwaves, (including in the form of electron cyclotron resonance), helicon waves, or DC means with and without a heated filament as an electron source. In Figure 1 an antenna 10 is shown located around a cylindrical tube 11 of dielectric material, through which RF power (from a supply point 21) is inductively coupled into the plasma formed inside the tube. The tube geometry can be other than that shown, for example square or

hexagonal or other shape in cross-section. The geometry may alternatively take the form of a cone 11A, truncated cone 11B or hemisphere 11C or combination of these geometries (Figure 3). In most circumstances, one antenna 10 will be used to couple power into the plasma. However, the uniformity of the etch or deposition process may be improved by the use two or more antennae 10A, 10B, particularly if they are located around different diameter sections of the dielectric tube 11 (Figure 3B).

The dielectric material from which the tube 11 is formed may be alumina or quartz or other suitable material compatible with the process gases. It may be advantageous to use a material such as silicon carbide, which has higher thermal conductivity than alumina, and therefore enables better transference of heat from the internal walls, adjacent to the plasma, to external cooling means. Because of its higher electrical conductivity, silicon carbide may assist in reducing the capacitive coupling of RF power into the chamber when inductive coupling is the desired mode. Aluminium nitride is an alternative material, combining high thermal conductivity with low electrical conductivity, and allowing good heat transference but with little effect on the coupling of RF power from an external antenna 10 into the plasma. When the plasma density is high, the high thermal conductivity of either aluminium nitride or silicon carbide can be a particular advantage. This is because the temperature gradient between the inside and outside of the

tube is reduced compared with a material with less good thermal conductivity such as alumina, and therefore differential expansion of the tube is reduced. Significant differential expansion of the dielectric tube can lead to crack formation and propagation, with loss of vacuum integrity.

In some circumstances there may be advantages in terms of the uniformity of processing of the wafer, to use a geometry (see Figure 5) in which chamber A is formed of two, or more, differing-diameter cylindrical dielectric sections 11X, 11Y. RF power is then coupled into the plasma by two, or more, separate antennae 10A, 10B each located around the respective cylindrical sections. This may be constructed out of one piece of dielectric material, or may consist of two, or more, separate sections 11X, 11Y with a conducting or non-conducting interface flange 12 with appropriate vacuum sealing means. Although cylindrical sections are described, this is not to preclude other geometrical shapes such as those with square or hexagonal cross-sections. The two, or more, separate antennae would utilise separate impedance matching units and either separate RF power supplies or a split output from a single supply. With reference to Figure 5, the power coupled into the plasma via antenna 10A has more effect on the ion and radical fluxes reaching the centre of the wafer, while the power coupled into the plasma via antenna 10B has more effect on the ion and radical fluxes

reaching the outer region of the wafer. Lateral diffusion of ions and radicals means that the above effect is not clear cut, but is essentially true if the distance between the upper chamber A, and the wafer is not too great. Adjustment of the relative levels of RF power fed to the two, or more, antennae would allow adjustment of the plasma profile within this chamber, and of the effect of the plasma at the wafer. Relative power levels could be adjusted to different values depending on whether an etch step or a deposition step was in progress.

With reference to Figure 1, the upper chamber A is formed out of the dielectric cylinder 11 defining the side walls, with the top closed by plate 13 with suitable vacuum sealing means to the cylinder. The top plate will normally be constructed out of metal, with a suitable connection 14 to allow process gas to be fed into the chamber. Suitable means may be incorporated to distribute the gas uniformly in the chamber. A window (for example as at 15 in Figure 4 or Figure 5) may be incorporated in the top plate to allow observation of the plasma and/or wafer for process end-point measurements etc. The lower end of the dielectric cylinder interfaces with the lid 17 of the lower chamber B, either directly or with an intermediate short pipe section, usually formed of metal, which may be grounded or allowed to float electrically or biased to a chosen potential.

Although the above description includes the feeding of process gas through the lid of the upper chamber A, it may

under certain circumstances be desirable, additionally or alternatively, to feed gas back up into this chamber from a gas ring 16 mounted within the lower chamber B, near the lid 17 of the lower chamber. In some circumstances one gas may be fed through the lid of the upper chamber A and a different gas may be fed from the gas ring mounted within the lower chamber B. Where the geometry of the upper chamber is a hemisphere or cone, manufactured entirely out of dielectric material, then it will not be possible to feed gas into the top of the upper chamber A and a gas ring 16 within the lower chamber is then essential.

When a switched process is used, there may be advantages to feeding the appropriate process gas through either the inlet in the lid of the upper plasma chamber A, or through the gas inlet ring in the lower process chamber B, depending on whether the etch step or the passivation step is being executed. Alternatively it may be desirable to feed gas via both routes for one step and only one route for the other step. Whichever route is used to feed the process gas into the apparatus during each of the two steps, appropriate control of the inlet gas flows may be by means of mass flow controllers. An automatic pressure control valve (APC) may be used to control the gas conductance from the process chamber to the vacuum pumps, and this will allow the process chamber pressure to be controlled.

In some circumstances it may be desirable to utilise significantly different pressures in the process chamber for each of the two steps in a switched process. For example, high pressure during the etch step and low pressure during the passivation step. This can be achieved by suitable fast acting control of the mass flow controller(s) feeding gas into the chamber and the pressure control valve controlling the gas conductance between the chamber and the vacuum pumps.

For a plasma to be formed in the upper chamber A, RF power must be applied to the antenna 10 surrounding the upper chamber with the required process gas introduced via the relevant inlet means. Neutral radicals are formed by energetic electrons from the plasma impacting on the neutral gas and, therefore, within the upper chamber A, ions, electrons, radicals and un-dissociated feed gas will exist. All of these species will diffuse into the lower chamber B, with some losses in numbers due to re-combination in the volume and at the walls. Ions and electrons will re-combine readily at the walls of the chamber; however radicals may survive a number of collisions. When magnetic confinement is present in the lower chamber B, the loss of ions and electrons to the walls of this chamber can be significantly reduced.

Restriction of the size of the aperture in the lid 17 of the lower chamber B, where the upper chamber A is mounted, or the internal diameter of the intermediate short

pipe section when present, will allow a higher pressure differential to be maintained between the upper chamber and the lower. This may increase the process efficiency because the higher pressure in the upper chamber can benefit the formation of ions and radicals because of increased collisions, while a reduced pressure in the lower chamber reduces the incidence of re-combination within the volume. This arrangement can clearly only be utilised when there is a gas feed into the upper chamber, and may have detrimental results if losses of ions or radicals at the restriction are increased. A variable aperture automatic pressure control (APC) arrangement may be incorporated at this position. However the physical design of the APC may reduce the uniformity of the ion flux, in particular, reaching the wafer.

If desired, a dipole magnetic field, either formed by the use of permanent magnets 8 or an electromagnet, may be applied across the lower end of the upper chamber A (or across the intermediate short pipe section when present), to form a magnetic plasma attenuator. The permanent magnets or electromagnets used to create the field will generally be located outside of the chamber, but may be partially or wholly internal to the chamber. The action of this field is to deflect electrons, and thence ions, to the wall where they are lost, and therefore to allow control of the numbers of ions passing into the lower chamber, whilst not reducing the radical flux.

If the magnet structure is inside the chamber, then by its geometry it will be expected to increase slightly the local loss area for radicals. Control of the relative numbers of ions compared with radicals, passing into the lower chamber, allows greater control of the overall process. In particular for a switched process, if an electromagnet or hybrid of a permanent and an electromagnet is utilised, then it is feasible to control the relative numbers of ions to radicals to different appropriate ratios for each of the two steps.

Control of the RF power into the plasma in the upper chamber A determines the numbers of ions and radicals formed, and in general both will increase with increasing power input. Process gas flow and pressure will also have an effect. There is increasingly a need to produce higher etch rates, which for chemical reactions requires large numbers of radicals while the numbers of ions may need to be restricted to reduce unwanted damage to the etched structure or the mask. The combination of control of the plasma density to produce large numbers of ions and radicals, in conjunction with a "magnetic plasma attenuator" to reduce the ion component reaching the wafer, permits high, predominantly chemical, etch rates to be achieved with reduced ion-associated detrimental effects. Detrimental effects associated with high ion fluxes to the wafer include high mask etch rates and problems in sidewall profile control of etched features.

The dipole form of "magnetic plasma attenuator" has a drawback in that the application of a magnetic field across the upper chamber leads to a perpendicular deflection of ions and electrons such as to reduce the cylindrical symmetry of the ion flow from the region in which the plasma is formed, down towards the wafer. This may reduce the uniformity of the process carried out on the wafer.

A solenoidal magnetic field generated by a coil 18 around the upper chamber A, as shown in Figure 4, has advantages as a "magnetic plasma attenuator", over the dipole field described above. Cylindrical symmetry is maintained while, by judicious adjustment of the magnetic field strength, a dense plasma region 19 formed inside the tube 11 and adjacent to the antenna 10 is at least partially trapped by the field lines 20. These field lines intersect the wall of the upper chamber A near or on the lid 13, and either on the upper chamber wall near its base, or on the lid 17 or upper walls of the lower chamber B. The omission of a magnet 8 (creating a dipole field) removes a possible source of non-uniformity of the plasma. Significant numbers of radicals can be created in the upper chamber A, which then diffuse into the lower chamber. The associated ion flux is reduced, however, because of losses where the field lines intersect the walls, thereby ensuring that the ratio of ion numbers to radical numbers reaching the wafer is reduced in line with requirements. As shown in Figure 5 there may be separate solenoids 18A, 18B

provided for each of the sections 11X and 11Y, which allow for greater control of the plasma. As can be seen separate dense plasma regions 19A and 19B are created by the two antennae.

When magnetic confinement is provided in the lower chamber B, some electrons trapped on magnetic field lines from the solenoid 18 around the upper chamber A, may encounter the strong magnetic fields at the walls of chamber B. This may lead to some local mirroring of the electrons so that they may survive to take part in further excitation and ionisation collisions with gas molecules. The situation may occur therefore where the strength of the field from the solenoid around the upper chamber A is sufficient to reduce significantly the flux of ions to the wafer 1, whilst at the same time excitation and ionisation collisions are increased. An increased rate for radical formation by this mechanism has the potential to increase the rate of chemical etching of the wafer.

Experimental operation has been carried out, of a de-coupled plasma source and process chamber incorporating some of the features described already. The arrangement was as shown in Figure 6. The chamber A, in which the plasma was generated, consisted of a dielectric tube 11 with an RB antenna 10 located around its centre section and held in this position by suitable support means. RF power from the RF power supply 21 was fed to the antenna via a matching unit 22, which matched the plasma impedance to the

50 ohm impedance of the power supply. An electromagnetic solenoid 18 was positioned around the plasma chamber A so that, when energised, a magnetic field pattern was produced as indicated by the representational magnetic field lines 20. This electromagnetic solenoid 18 was the only form of magnetic ion attenuation incorporated on the de-coupled plasma source and process chamber arrangement. No form of dipole magnetic ion attenuator was incorporated between the plasma source and process chambers.

The process chamber B, incorporated a "magnetic bucket" (as in Figure 2) formed from small permanent magnets located around the perimeter, in order to improve the plasma confinement, but no electromagnet was operated around the process chamber, at or near the wafer processing height 6.

A particular experiment was carried out to determine the effectiveness of the solenoidal magnetic field, created by the electromagnet 18 around the chamber A, in which the plasma was formed, in attenuating the flux of ions reaching a wafer 1 mounted in the process chamber B. In this experimental work a silicon wafer was utilised as the workpiece, but it is to be understood that the workpiece could equally be a wafer of another material or an alternative object to be subjected to a plasma induced process.

A small Langmuir probe 23 was inserted through a port in the wall of process chamber B so that it could be moved

along a diameter of the chamber just above the surface of a test wafer which had been loaded into the chamber. The Langmuir probe was used to measure the ion flux immediately above the wafer as a function of position across the diameter of the chamber.

Experimental results of ion flux as a function of position across the diameter of the process chamber are shown in Figure 7. Each of the curves is for a different value of the current passed through the electromagnetic solenoid around chamber A in which the plasma was formed. The strength of the magnetic field increases as the current passed through the solenoid is increased. From the graph, it can be clearly seen that as the magnetic field strength is increased, the ion flux reaching the wafer processing height, is reduced and to some extent the magnitude of the ion flux becomes more uniform over a significant part of the chamber diameter.

The experimental measurements of ion flux carried out by means of the Langmuir probe have been reinforced by further experiments in which the use of the electromagnetic solenoid around the chamber A has reduced ion-associated effects on wafers being processed, while allowing high chemical etch rates to be obtained.

The use of an electromagnetic ion attenuator is an effective way of reducing the ion flux reaching a wafer while allowing a high neutral radical flux to reach the wafer. This is clearly a useful facility when an etch

process is primarily chemical, and so driven by the radical flux, but the mask is primarily eroded by the flux of ions reaching it.

In some circumstances it may be desirable to reduce the proportion of ions reaching the wafer surface when compared to the numbers of neutral radicals, to levels which are lower than that which can be achieved by magnetic attenuation alone. Alternatively, there may be reasons for not wishing to operate the magnetic attenuator at high field strengths. A method of achieving the required result for certain processes is to pulse on and off the plasma formed in chamber A, at the same type as operating the magnetic attenuation means.

In the specific case of the etching of silicon by the gas $SF_6$ it is understood that the etching of the silicon is primarily due to a chemical reaction of the fluorine radicals formed in the plasma. It is also known that for certain operating conditions, the fluorine radicals that are formed by the plasma can exist for a significant length of time after the plasma has been extinguished. The ion density, however, usually decreases very quickly after the plasma is switched off. This difference in lifetimes of the two species can be used to advantage if the plasma is pulsed on and off at a suitable rate and with an appropriate pulse mark space ratio. Boswell and Porteous [J. Appl. Phys. 62(8), American Insti. Of Phys. 1987] describe the pulsing of an $SF_6$ plasma in which, for 2

millisecond pulses with a 10 millisecond period, the mean silicon etch rate is essentially the same as the rate for a continuous plasma. The lifetime of the charged species was found to be less than 1 millisecond, which is typical of this kind of low pressure discharge. For the pulsed plasma alone, the results of Boswell and Porteous indicate that he ratio of time-averaged ion flux to radical flux may be reduced to less than 0.3 times the ratio in a continuous plasma. It can therefore be anticipated that the combination of a pulsed plasma with the magnetic attenuator concept has the potential to reduce the ratio of ion flux to radical flux reaching the wafer to a value which is smaller than either technique in isolation.

The de-coupled plasma source and wafer processing chamber shown in Figure 1 or Figure 6 can be used to great effect for carrying out certain processes on certain sized wafers. In general, the neutral radicals formed in the plasma source diffuse down to the wafer where they react chemically with the surface. The ion flux reaching the wafer surface can be controlled by the use of the magnetic attenuation means and if necessary by the pulsing of the plasma in the source. While the use of an electromagnetic solenoid ion attenuator 18 around the plasma source acts to reduce the flux of ions reaching the wafer, and to some extent assists in making the ion flux more uniform across the wafer, the simple de-coupled source may have some limitations due to its geometry.

In order to form an efficient high-density plasma in the source for acceptable levels of applied RF power, its volume should be reasonably small. The electromagnetic solenoid around the source can then also be reasonably small, with low current requirements. The neutral radicals formed in the source diffuse down to the wafer and the flux reaching the wafer as a function of radius, is determined in part by the geometry of the plasma chamber, but also by vacuum pumping arrangements for the process chamber and any baffle systems.

The ion flux magnitude and uniformity at the wafer surface is determined by the magnetic attenuator, but also by the geometry of the source chamber and whether magnets are located on the perimeter of the process chamber B to enhance the plasma confinement. For a small diameter plasma source compared with the diameter of the wafer, it may be difficult to maintain a near uniform ion flux to the wafer from the centre of the wafer out to the edge. For a single de-coupled source on the same axis as the wafer, the ion flux density to the wafer is likely to decrease from the centre to edge.

In many cases a small gradient in the ion flux density between the centre of the wafer and the edge will not cause any appreciable problem, particularly if the process is predominantly chemically driven. In those circumstances, where the process is ion driven or depends on a well defined ion flux impinging on the wafer perpendicular to

the wafer surface for at least part of the process, the uniformity and directionality of the ion flux may not be sufficient with the processing apparatus geometry described above. If this is the case, further measures may need to be taken to improve the uniformity of the ion flux reaching the wafer.

A particular configuration of the plasma processing equipment designed to help to reduce the problem described above is shown in Figure 8. This arrangement is based around the use of a de-coupled source of similar form to that described in earlier parts of this document. Plasma is formed in the smaller source chamber A with neutral radicals diffusing down into the process chamber B in which the wafer is supported. Ions from the plasma also diffuse into the process chamber, but a magnetic ion attenuator 18 is operated to reduce the ion flux as required. Magnetic plasma confinement may be utilised on parts of the walls of the process chamber B in order to improve the uniformity of the ion flux to the wafer.

Where the alternative configuration of the de-coupled processing apparatus differs from that described previously is that a secondary plasma is formed within the process chamber by the use of the RF power coupled in by an antenna 24 around the upper section of the process chamber B. This description of the inductive coupling of RF power into a secondary plasma is given by example and is not intended to preclude the generation of a secondary plasma within the

process chamber by other means, for example by capacitive coupling of RF power, or by the use of microwave power.

An antenna around the upper section of the process chamber B forms an annular plasma within the chamber, which then diffuses throughout the chamber volume. In general the power supplied to this antenna will be considerably less than that supplied to the antenna 10 around the smaller source chamber A. The prime purpose for the formation of this secondary plasma is to provide additional ions near the edge of the plasma chamber, thereby increasing the flux of ions towards the edge of the wafer. By careful adjustment of the power fed to this secondary plasma the additional ions can make up for the shortfall in the ion flux towards the edge of the wafer arriving from the source chamber A, after passage through the magnetic ion attenuator 18. While in most cases the secondary plasma is used to increase the ion flux towards the edge of the wafer, and the extra radicals produced are of lesser importance, there may be occasions when these extra radicals are of benefit to the process being performed. If required, it would be feasible to place a solenoidal magnetic ion attenuator around the section of the process chamber B where the antenna 24 is located, and then control the relative numbers of ions and neutral radicals emerging into the main volume of the process chamber.

For the alternative configuration of the de-coupled source plasma processing apparatus described above, the

process gas will generally be fed in through the inlet 14 in the lid of the plasma chamber A. However, it alternatively may be fed in through a gas ring 16 located inside the process chamber B, near its lid. In some circumstances the process gas may be fed via both inlets 14 and 16 simultaneously, or different gases may be fed via either route.

When a switched process is being carried out, the gas may be fed to either one or both of inlets 14 and 16 depending on which step is taking place. For example, when the etch step is carried out, gas may be fed primarily into the top of the plasma chamber A through inlet 14, where it is subjected to the dense plasma to produce copious numbers of etch radicals. When the passivation step is carried out, gas may be primarily fed in via the gas ring 16, and the antenna 24 around the upper section of process chamber B is then used to form the plasma, with no plasma or a weak plasma formed in chamber A. This example describes one possible scenario, and is not intended to limit in any way the options for the gas feed route or region in which the plasma is generated for either step of a switched process.

As described previously for the basic de-coupled source apparatus, the pressure in the process chamber B may be controlled to be significantly different during each of the two steps of a switched process.

While the above description has been for an antenna 24 outside and around the upper portion of the process chamber

B to couple power into a secondary plasma, this does not preclude the use of a suitably insulated and supported antenna located within the process chamber. To serve the same purpose as the externally mounted antenna, this internally mounted antenna would generally be located on a large diameter in the vicinity of the perimeter of the process chamber. The internally mounted antenna would require suitable feed through connections in one of the walls of the process chamber to allow the connection of RF power and possibly for the circulation of a cooling medium through a hollow antenna.

A further version of a de-coupled source plasma processing apparatus incorporating magnetic ion attenuation means is shown in Figure 9. In this arrangement the process chamber is essentially as shown in Figure 1 or Figure 6, but the plasma source chamber differs. In this case, the plasma source is of annular form, utilising one antenna 101 positioned radially outside of the outer dielectric cylinder 111 and a second antenna 102 positioned radially inside of the inner dielectric cylinder 112. These two antennae may be supplied by RF power from two separate power supplies or by one power supply using a suitable power splitting device. In some circumstances there may be advantages in adjusting the relative power fed to each antenna for fine adjustment of the plasma characteristics, but it is considered that in most

circumstances the two antennae would be driven together with a fixed power ratio.

Two electromagnetic solenoids are incorporated into the structure, one 181 is located radially outside of the outer antenna 101 and the other 182 is located radially inside of the inner antenna 102. By suitable adjustment of the flow of current in each of these solenoids, an electromagnetic ion attenuator can be formed for the annular plasma source. It should be noted that in order to form the magnetic field line pattern 20 shown in Figure 9 (which is effective in attenuating the ion flux reaching the wafer), the current flows in the two solenoids 181 and 182 must be such as to produce opposing field directions within each solenoid. In order to achieve the required field strengths from each of the two solenoidal electromagnets, each may be driven from a separate current source. However, in many circumstances it may be preferable to use a single current source with current division between the solenoids in a predetermined ratio to achieve the required ratio of magnetic field strengths.

There is a potential advantage of using the annular plasma source for the de-coupled source plasma processing apparatus when large wafers are to be processed, rather than the simpler small cylindrical plasma chamber. This is because the geometry ensures that radicals and ions enter the process chamber from the plasma chamber at larger diameters and by judicious choice of wafer processing

height, the different diffusion characteristics can be used to advantage. This may be particularly important for achieving a uniform flux of ions to the surface of the wafer.

The above structure has been described in terms of a cylindrical annular form; however, this is not intended to preclude similar structures having square, hexagonal or other multisided annular forms.

To someone skilled in the art, it would not be unreasonable to consider repeating this annular plasma source structure of Figure 9 at two or more different diameters and in one or more planes, if there was a need to feed ions and radicals into a large process chamber. The combination of an annular plasma source of suitable diameter with a simple cylindrical plasma source on the axis of symmetry may have application in certain circumstances.

While it is considered unlikely that it will be necessary to provide an additional antenna around the upper section of the process chamber B when an annular plasma chamber is used, this option may still be considered if desirable.

When operating the equipment to carry out a process within apparatus of the invention, it is possible for the field strength of any one or more electromagnets employed to create an attenuation magnetic field to be varied as a

function of time, thus altering the time variability of the ion attenuation.

CLAIMS

1. A plasma processing apparatus comprising a first chamber provided with a plasma inducing device designed to produce a plasma in said first chamber, and a second chamber into which plasma so produced can diffuse to act upon a workpiece being processed, and a magnetic field production device positioned relative to at least the first of said two chambers and constructed to cause attenuation of the ions which diffuse into the second chamber and approach the workpiece, by directing a proportion of the ions to a loss surface of either chamber.

2. Apparatus according to claim 1, wherein the magnetic field production device comprises permanent magnets or electromagnets installed around the side wall of the first chamber.

3. Apparatus according to claim 1 or claim 2, wherein the magnetic field production device around the first chamber is a solenoid whose output can be varied.

4. Apparatus according to any one of claims 1 to 3 and incorporating an additional plasma inducing device at the upper region of the second chamber.

5. Apparatus according to claim 4, wherein permanent magnets, electromagnets or a solenoid are installed also around said additional plasma inducing device at the upper region of the second chamber, as a further magnetic field production device

6. Apparatus according to any one of claims 1 to 5, wherein the magnetic field production device comprises a magnetic structure formed at the junction of the two chambers to create a dipole magnetic field there.

7. Apparatus according to any one of claims 1 to 6, and incorporating a ring gas feed within the second chamber, below the junction point of the two chambers, in addition to a gas feed inlet to the top of the first chamber.

8. Apparatus according to any one of claims 1 to 7, wherein a solenoid device whose output can be varied is provided for the second chamber at a position to create a magnetic field inside the second chamber at the level of the workpiece to steer ions towards the workpiece.

9. Apparatus according to any one of claims 1 to 8, wherein the second chamber is provided with a magnetic bucket arrangement created by an array of magnets around the chamber wall.

10. Apparatus according to any one of claims 1 to 9, wherein the first chamber geometry is formed as a cylinder, a stepped cylinder, a cone, a truncated cone, or a hemisphere, or a combination of these geometries.

11. Apparatus according to any one of claims 1 to 10, wherein the first chamber is of annular form and the annular magnetic field production device comprises separate permanent magnets, electromagnets or solenoids located both within and around said annulus.

12. Apparatus according to claim 11, wherein further annular forms of a first chamber with pairs of attenuation magnetic field production devices and with plasma inducing devices are positioned concentrically of one another.

13. Apparatus according to any one of claims 1 to 12, wherein the first chamber is formed of two or more differing-diameter cylindrical dielectric sections, one above the other, each such section being provided with its own plasma inducing device.

14. A plasma processing apparatus comprising a first chamber provided with a plasma inducing device designed to produce a plasma in said first chamber, and a second chamber into which plasma so produced can diffuse to act upon a workpiece being processed, wherein the first chamber is formed of two or more differing-diameter cylindrical dielectric sections, one above the other, each such section being provided with its own plasma inducing device.

15. Apparatus according to claim 13 or claim 14, wherein the portions joining the individual sections of said first chamber are formed of metallic or dielectric material.

16. Apparatus according to any one of claims 13 to 15, wherein the portions joining the individual sections of said first chamber are positioned perpendicular to or angled to said sections.

17. Apparatus according to any one of claims 13 to 16, wherein the multi-section first chamber has a magnetic field production device associated with more than one of

said sections, each constructed to cause attenuation of the flux of the ions which diffuse into the second chamber and approach the workpiece.

18. Apparatus according to any one of claims 1 to 17, wherein said first chamber incorporates a dielectric plasma tube formed from aluminium nitride or silicon carbide or other dielectric material having a thermal conductivity sufficiently greater than aluminium oxide to allow high power operation without failure-inducing high thermal gradients arising in the dielectric material.

19. Apparatus according to any one of claims 1 to 18, wherein a plurality of said first chambers are provided across the top of the second chamber.

20. A plasma processing apparatus comprising a first chamber provided with a plasma inducing device designed to produce a plasma in said first chamber, and a second chamber into which plasma so produced can diffuse to act upon a workpiece being processed, wherein said first chamber incorporates a dielectric plasma tube formed from aluminium nitride or silicon carbide or other dielectric material having a thermal conductivity sufficiently greater than aluminium oxide to allow high power operation without failure-inducing high thermal gradients arising in the dielectric material.

21. A method of controlling the transmission of a plasma to a workpiece, wherein plasma is created in a first chamber provided by a plasma inducing device, and is

allowed to diffuse into a second chamber to act upon a workpiece being processed, and an attenuation magnetic field production device positioned relative to at least the first of said two chambers is operated in a manner to cause attenuation of the ions which diffuse into the second chamber and approach the workpiece, by directing a proportion of the ions to a loss surface of either chamber.

22. A method according to claim 21, wherein said attenuation magnetic field is produced by permanent magnets, electromagnets, or a solenoid whose output can be varied, positioned around the side wall of the first chamber.

23. A method according to claim 21 or claim 22, wherein plasma is also created at the upper region of the second chamber by an additional plasma inducing device.

24. A method according to claim 23, wherein an attenuation magnetic field is additionally produced by permanent magnets, electromagnets, or a solenoid located around said additional plasma inducing device at the upper region of the second chamber, as a further magnetic field production device, to cause attenuation of the ions which diffuse further into the second chamber.

25. A method according to any one of claims 21 to 24, wherein said attenuation magnetic field is produced by a magnetic structure formed at the junction of the two chambers to create a dipole magnetic field there.

26. A method according to any one of claims 21 to 25, wherein gas is fed into a ring gas feed within the second chamber, below the junction point of the two chambers, in addition to gas fed through a gas feed inlet to the top of the first chamber.

27. A method according to claim 26, wherein different gases are fed into said gas feed inlet and said ring gas feed.

28. A method according to claim 26 or claim 27, wherein the inlet gas flows to the gas feed inlet and the ring gas feed are controlled by separate mass flow controllers.

29. A method according to any one of claims 26 to 28, wherein the process chamber pressure is set to different levels for each of different processing steps.

30. A method according to any one of claims 21 to 29, wherein the first chamber is constructed from two or more differing-diameter cylindrical dielectric sections and RF power is coupled into the plasma created in the first chamber by two or more separate antennae, each located around the respective cylindrical sections.

31. A method according to claim 30, wherein the relative power levels to the two or more antennae are adjusted to different values depending upon whether an etch step or a deposition step in a switched process is in progress.

32. A method according to any one of claims 21 to 31, wherein the plasma inducing device is operated so as to

pulse the plasma on and off during operation of the process.

33. A method according to any one of claims 21 to 32, wherein magnetic confinement is provided in the second chamber by means of a magnetic bucket arrangement created by an array of magnets around the chamber wall.

34. A method according to any one of claims 21 to 33, wherein the field strength of any one or more electromagnets employed to create an attenuation magnetic field is varied as a function of time.

35. Apparatus or a method for plasma processing substantially as herein described with reference to the accompanying drawings.

36. Any novel combination of features of apparatus or method for plasma processing as described herein and/or as illustrated in the accompanying drawings.

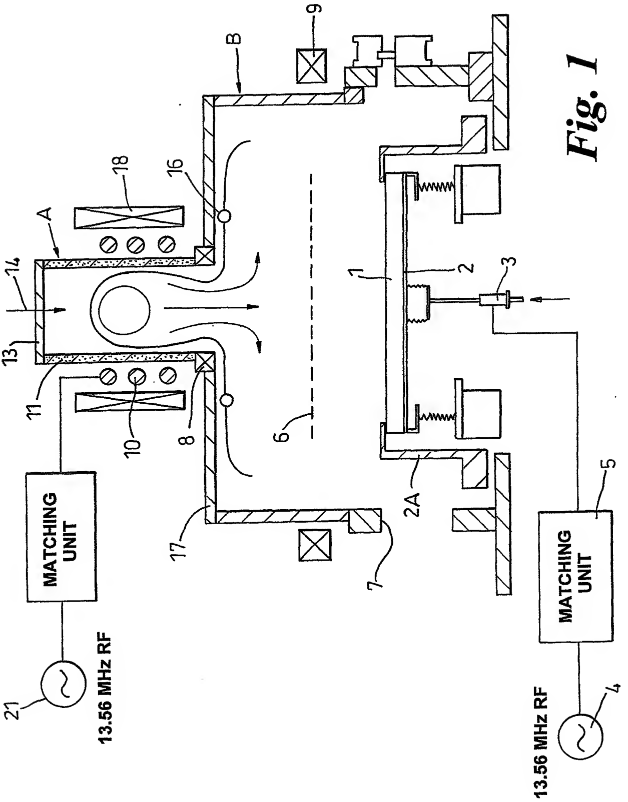
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Fig. 1

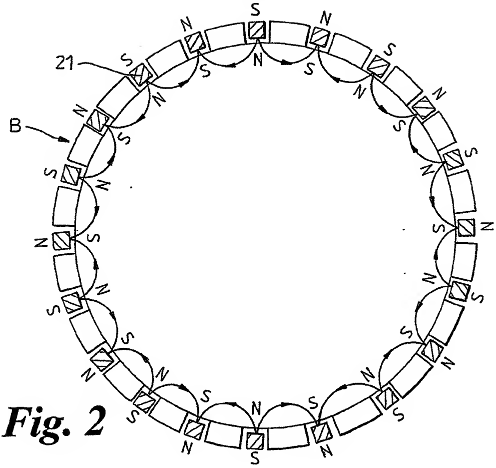


Fig. 2

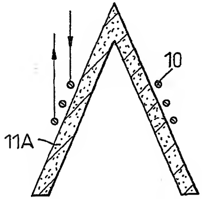


Fig. 3A

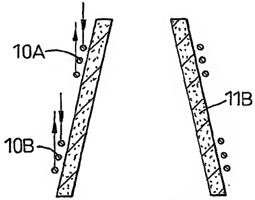


Fig. 3B

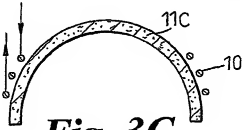


Fig. 3C

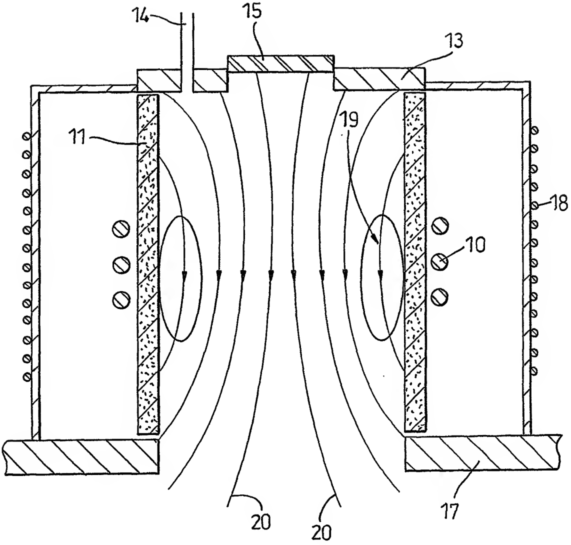


*Fig. 4*

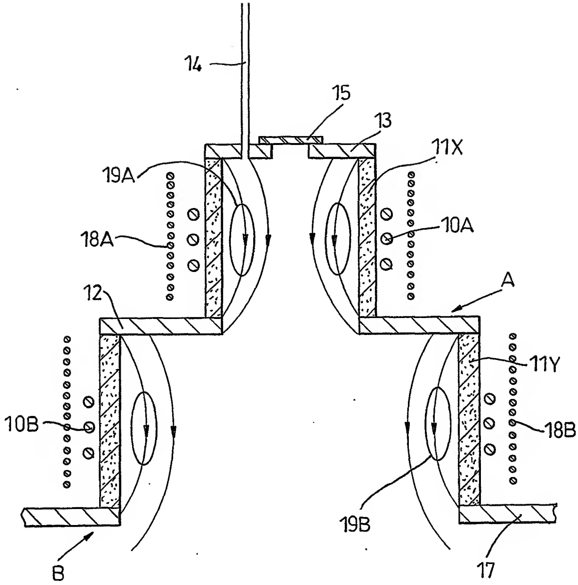


*Fig. 5*

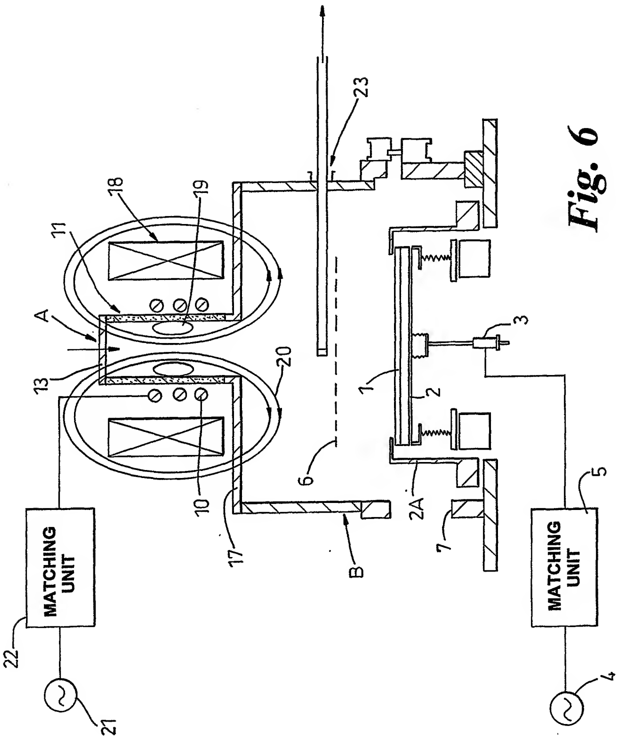
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Fig. 6

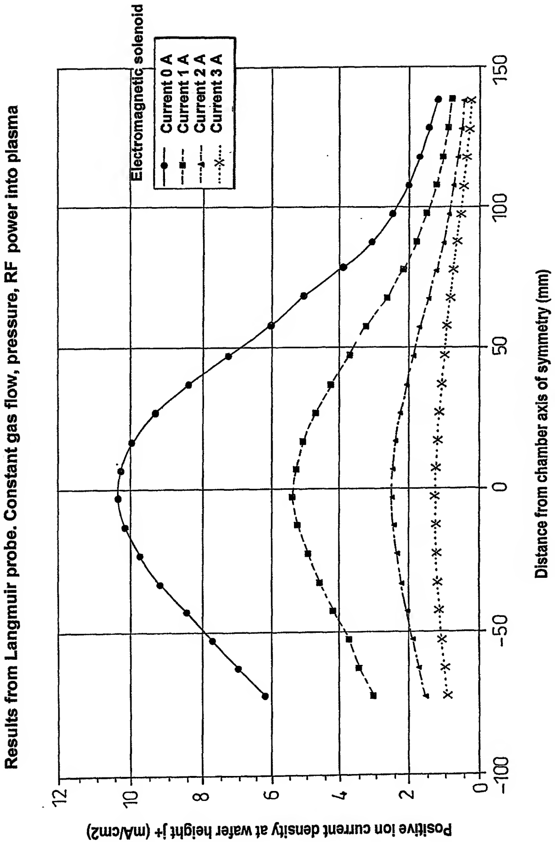
Results from Langmuir probe. Constant gas flow, pressure, RF power into plasma
Electromagnetic solenoid
Current 0 A
Current 1 A
Current 2 A
Current 3 A
Positive ion current density at wafer height j+ (mA/cm2)
Distance from chamber axis of symmetry (mm)
0
2
4
6
8
10
12
-100
-50
0
50
100
150

*Fig. 7*

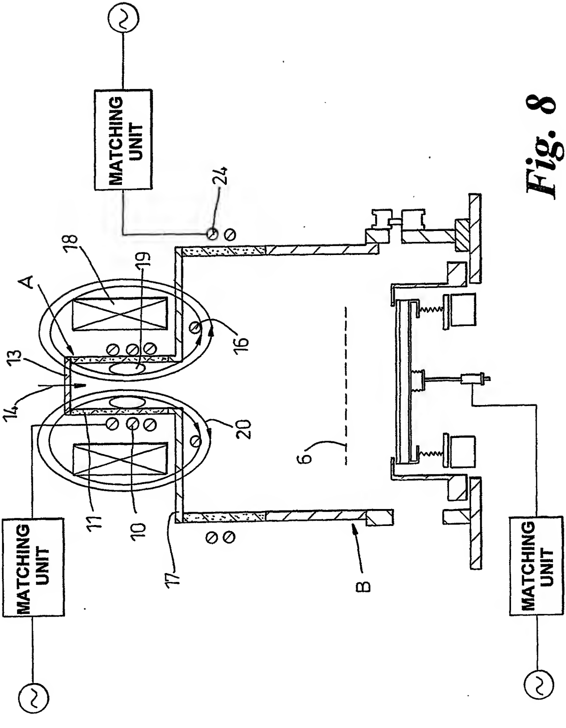
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Fig. 8

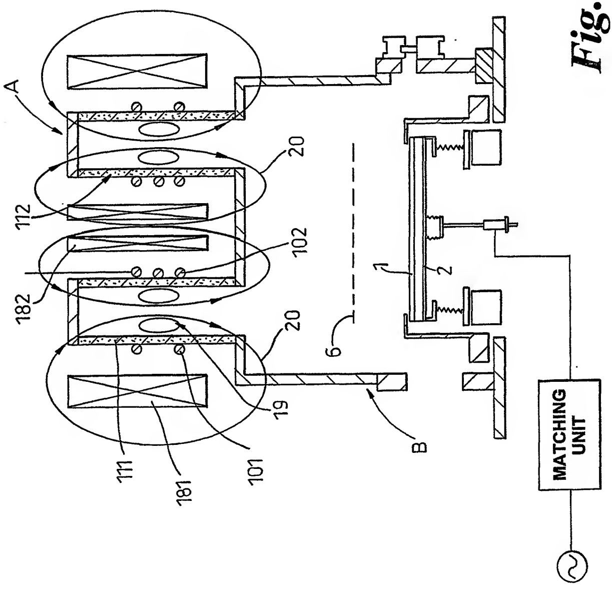


*Fig. 9*

# INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 02/00115

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 7 H01J37/32

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, PAJ, EPO-Internal, INSPEC

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | PATENT ABSTRACTS OF JAPAN vol. 1999, no. 10, 31 August 1999 (1999-08-31) & JP 11 135297 A (KUMAGAI HIROMI), 21 May 1999 (1999-05-21) abstract & DATABASE WPI Section Ch, Week 9931, 21 May 1999 (1999-05-21) Derwent Publications Ltd., London, GB; Class L03, AN 363023 abstract | 1-6,10, 14-17, 19,21, 22,25 |

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 4 June 2002 | 13/06/2002 |

| Name and mailing address of the ISA | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL – 2280 HV Rijswijk<br>Tel. (+31–70) 340–2040, Tx. 31 651 epo nl,<br>Fax: (+31–70) 340–3016 | Schaub, G |

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# INTERNATIONAL SEARCH REPORT

In tional Application No
PCT/GB 02/00115

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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| X | EP 0 552 491 A (APPLIED MATERIALS INC)<br>28 July 1993 (1993-07-28)<br><br>page 15, line 25 -page 16, line 3; figures<br>2,3,13 | 1-7,9,<br>14-17,<br>20-22,<br>26,33 |

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Information on patent family members

International Application No
PCT/GB 02/00115

| Patent document cited in search report | | Publication date | Patent family member(s) | | Publication date |
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